Dynamic-Range Penalty of Analog Optical Feeders for Fiber-Optic Microcellular Systems in the Presence of Co-channel Interference and Multipath-Fading

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Abstract

The dynamic range of the optical feeder in the fiber-optic microcellular system is one of the key parameters in determining the feasibility and cost-effectiveness of the system. Recent simulation results [1] have considered the carrier power variation due to different propagation losses only. However, in the more practical wireless environment, due to cochannel interference and multipath fading, a dynamic range penalty is imposed. We present the simulation results which show that the required dynamic range of the fiber-optic link is tightened by about 4 dB in a microcell with 100m radius in the presence of cochannel interference and multipath fading. The dynamic range requirement can be relaxed by means of automatic gain control at the base station and simulation results show that about 10 dB improvement in dynamic range can be achieved. Such results are quite important in designing a cost-effective and practical fiber-optic microcellular system for future personal communications networks.

I. Introduction

Nowadays, the demand for personal communication grows tremendously and thus wireless cellular systems are becoming more and more popular throughout the world. The number of mobile users has been increasing drastically, especially in urban areas. In order to provide the service to more users, cell splitting is one of the feasible ways to increase the frequency reuse and thus provides more channels to the users. Therefore, wireless microcellular systems have attracted much attention and interest. The cell size of such system is about a few hundred metres and thus it requires less radio transmitter power but still serves a high density of users. In each microcell, there is one base station having an omni-directional antenna to receive and transmit the uplink and downlink traffic to and from the mobile users. Sometimes, directional antennas may be used to perform sectorization within the cell so as to achieve more frequency reuse. These base-stations will be connected to the central switch for call processing.

The recent great improvement in the linearity of the optical components has aroused the interest of using analog fiber-optic link as the feeders in microcellular systems [2;3;4] since optical feeder offers many advantages. It can provide a low loss transmission medium and thus the required power is reduced. Moreover, it can also reduce the system complexity since the RF carriers need not to be downconverted to baseband before transmitting to the central switch station. This can reduce the size of the antenna module and make the selection of the installation location more flexible. Furthermore, it offers high capacity and thus can serve areas with high user density. In order to design the system in the most feasible and cost-effective way, we have to consider the feeder requirement according to the operating environment. The dynamic range of the optical feeder is an important consideration for such system's practicality. If the dynamic range is not good enough to serve the traffic in the microcell, the voice quality of the calls would be much degraded by noise, distortion and fading. Calls with unacceptable voice quality will be blocked by the base station in order to ensure the quality of service. In [1], it is shown that an 85 $dB \cdot Hz^{\frac{2}{3}}$ dynamic-range link is needed for a 300-m microcell with 50 channels. The results reveal the feasibility and practicality of such system. However, in their simulation, cochannel interference and multipath fading which are the two most important environmental factors, have not been considered. These two factors definitely degrade the system and thus impose a dynamic range penalty to the fiber-optic link.

In this paper, a more accurate and practical estimation of the dynamic range requirement of the analog fiber-optic is studied. The dynamic range penalty imposed by the cochannel interference and multipath fading will be discussed in section II. Simulation results will be presented in section III. Finally a feasible method in relaxing the tightened dynamic range requirement will be discussed in section IV.

II. Design Considerations of the Optical Feeders

In a fiber-optic microcellular system as shown in Figure 1, each microcell has a base station. These base stations are connected to the central switch by fiber feeders. There are two kinds of traffic, the uplink (from mobile to base station) and downlink (from base station to mobile). For the downlink, the variation of the transmitted power of each channel is small. For the uplink, the received power from different channels fluctuates greatly due the different propagation loss and multipath fading. Thus the noise and linearity requirement of the uplink is more stringent than the downlink. Since the channel bandwidth is usually small (in the order of kHz), the channels are usually operated within one octave and thus the dominant distortion components falling on the channels are the two-tone third order terms $(2f_i - f_j)$ and the triple-beat terms $(f_i + f_j - f_k)$ for distinct i, j and k. These distortion components definitely degrade the quality of the voice channels.

In the feeder design, one of the important factor is the dynamic range. It is the measure of the range of the carrier power levels in order to have acceptable distortion and noise performance. So, it is always limited by the linearity and noise of the optical transmitters and receivers. The dynamic range of an analog fiber-optic link is usually specified the range of input carrier powers over which the output is spur free for a two-tone input as shown in Figure 2. The relation between the dynamic range and the linearity can be derived from the plot of fundamental and two-tone third-order intermodulation products as shown in Figure 2. From the plot, we can obtain [2]:

$$DR = \frac{2}{3}(IP_3 - N) \qquad (1)$$

$$IP_3 = \frac{1}{2}(3P_c - P_{IM3}) \qquad (2)$$

where DR is the dynamic range in $dB \cdot Hz^{\frac{2}{3}}$, N is the noise floor in dB/Hz, P_c is the power level (in dBm) of the output carrier power, P_{IM3} is the power level (in dBm) of the output two-tone third order distortion term. The P_{IM3} is also related to the third-order nonlinear coefficient (k_3) of the system by considering the power series of the total output carrier power [5].

$$P_{IM3} = 3.52 + 20\log_{10} k_3 + 3P_c \qquad (3)$$

Therefore we can determine the required system's nonlinear coefficient (k_3) in order to achieve a certain dynamic range. Practically, since there is great variation in the channel carrier power levels, the distortion distribution among the channels also have great variation.

Thus, the dynamic range requirement derived from the above approach may not be accurate [1] and a dynamic range penalty will be imposed due to multipath fading and cochannel interference. Using the value of k_3 derived from Expression (3), the power of a two-tone third-order distortion component (P_{IM3}) falling onto channel f_r due to beating of channels f_i and f_j with ($f_r = 2f_i - f_j$) is:

$$\begin{aligned} P_{IM3}(r_{ij}) &= 3.52 + 20\log_{10} k_3 + 2P_c(f_i) \\ &\quad + P_c(f_j) \\ &\quad for\ distinct\ i, j,\ and\ r \qquad (4) \end{aligned}$$

On the other hand, the power of a triple-beat component (P_{TB}) falling onto channel f_r due to beating of channels f_i, f_j and f_k with ($f_r = f_i + f_j - f_k$) is:

$$\begin{aligned} P_{TB}(r_{ijk}) &= 9.54 + 20\log_{10} k_3 + P_c(f_i) \\ &\quad + P_c(f_j) + P_c(f_k) \\ &\quad for\ distinct\ i, j, k\ and\ r \qquad (5) \end{aligned}$$

where $P_c(i), P_c(j)$ and $P_c(k)$ are the power levels (in dBm) of the three carriers which contribute to the third-order distortion term. So, the aggregate third-order distortion falling on the r th channel can be obtained. Based on these relations, a series of simulation is done to determine a more practical dynamic range requirement for the fiber-optic microcellular system.

III. Simulation Model and Results

In the simulation model, the frequency reuse factor (K) is 7 as shown in Figure 1. The received power level variation of each carrier at the base station due to propagation loss is assumed to be proportional to D^{-4} where D is the distance of the mobile from the base station. We have studied the power variation due to the two outdoor environmental factors, the cochannel interference and multipath fading. For the cochannel interference, the effects from users in the first-tier and second-tier cochannel cells are considered. The effects from the other cochannel cells farther than the second-tier ones are not considered due to the high propagation loss. Now let us consider the multipath fading. In the microcell enviroment, especially in densely-populated urban area, there are many obstacles such as buildings which create much reflections of the radio waves. So, it is reasonable to assume the fading characteristics to be log-normal. In the simulation, we assume the channel bandwidth to be 30kHz. Users are assumed to be located randomly (uniformly-distributed) within the microcell. The received carrier powers are found to have great variation (about 40-60dB). They are then amplified before they are fed into an analog fiber-optic feeder to the central switch. At the optical transmitter side, the noise level is assumed to be -110dB/Hz. Then the intermodulation distortion (IMD) terms created at each channel due to the nonlinearity of the feeder are calculated. Since there is great variation in the power level of the channel carriers, the nonlinear distortion components falling onto each channel also vary greatly. Any channel having the carrier to interference/distortion (C/I) ratio less than 12dB is considered to have unacceptable quality and thus is blocked. This figure is within the C/I range used by some commercial cellular systems such as IS-54. The process is repeated for 5000 runs to obtain the call blocking probability for different feeder dynamic ranges. By setting the acceptable call blocking probability to be less than 0.5%, the minimum dynamic range required by the feeder can be determined.

The simulation results are shown in Figures 3, 4 and 5 and are tabulated in Table 1.

It is shown that in a microcell with 100m radius, the minimum required dynamic range is about the same (only about 0.2 dB penalty) in the presence of cochannel interference, while an extra 4 dB increase in dynamic range is required to achieve less than 0.5% call blocking probability in the log-normal fading environment. This shows the dynamic range penalty is mainly due to the multipath fading.

IV. Dynamic Range Improvement by Automatic Gain Control

From the simulation results, it seems that there is negligible (only about 0.2 dB) dynamic range penalty caused by the cochannel interference. It may be due to the fact that the distance between the base station in a microcell and that in the corresponding first-tier and second-tier cochannel microcell of a system with K=7 is too large and thus the propagation loss has much weakened their effects. On the other hand, it is shown the multipath fading severely increases the variation of the carrier powers and thus worsens the distortion performance. The dynamic range penalty is about 4 dB. Therefore, the optical feeder should be able to tolerate such degradation.

An simple way to relax the dynamic range requirement is to employ automatic gain control (AGC) in the uplink at the RF amplifier at the base station's receiving front end. This can automatically adjust the amplifier's gain to ensure a constant average power to be inputted to the optical feeder and the distortion level will be improved. From the simulation results as shown in Figures 3, 4 and 5, after using AGC, the dynamic range requirement is much relaxed by about 10 dB and thus this proves the efficiency of this approach.

However, due to the fading environment, the received signal power at the base station fluctuates severely with the characteristics of having fading nulls at about every half wavelength in space [6]. Within two adjacent nulls, the signal power is quite constant (see Figure 6). So, the AGC should be fast enough to adjust the gain within this period. Consider when the mobile is moving at x m/s, a rough estimation of the response time (t) of the AGC should be:

$$t = \frac{c}{2fx} \qquad (6)$$

where f is the carrier frequency and c is the speed of light. For example, when the user is moving at 50 km/h with carrier frequency at 900 MHz, the required response time of the AGC is about 12ms which is within the practical range of the common electronic circuits. So, such approach to improve dynamic range is feasible, efficient and practical.

Apart from using AGC, there are other methods to reduce the nonlinear distortion such as FM double modulation [7], frequency assignment scheme [8], and diversity schemes [6] to combat fading, etc. These methods are also feasible to alleviate the dynamic range penalty of the feeder. The criteria of the right choice are their efficiency and cost-effectiveness.

V. Conclusion

In conclusion, we have shown the dynamic range penalty due to cochannel interference and multipath fading for fiber-optic microcellular systems. From the simulation results, it is shown that the required dynamic range of the fiber-optic link is tightened by about 4 dB in the presence of cochannel interference and multipath fading in a microcell with 100m radius. The dynamic range requirement can be much relaxed by means of automatic gain control at the base station. Simulation results show that about 10 dB improvement in dynamic range can be achieved by using AGC. The relaxed link dynamic range requirement implies the required dynamic ranges of the devices such as transmitters and receivers can be reduced and so does the cost. These results are quite important in designing a cost-effective and practical fiber-optic microcellular system for future personal communications networks .

Number of Channels	Cell Radius (m)	Minimum Dynamic Range ($dB \cdot Hz^{\frac{2}{3}}$)			Dynamic Range Penalty (dB)
		without CI & MF	With CI only	With CI & MF	
5	100	70.6	70.9	74.5	3.9
10	100	77	77.1	81.2	4.2
20	100	81	81.2	85	4

Table 1: CI - Co-channel interference, MF - Multipath Fading

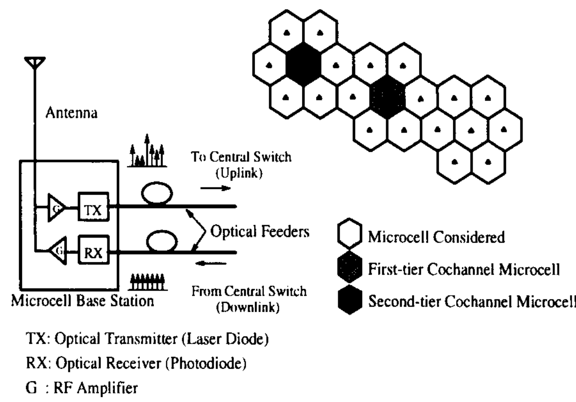

Fig. 1. A typical fiber-optical microcellular system with frequency reuse factor K = 7

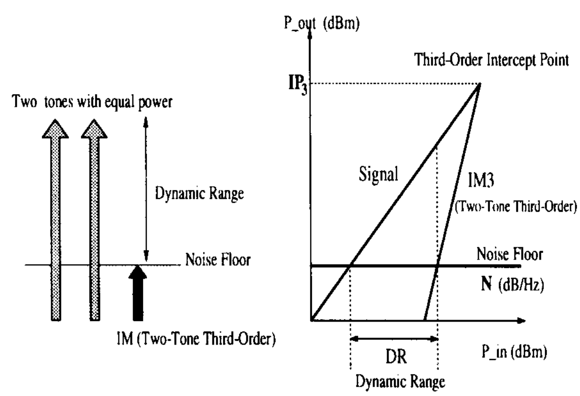

Fig. 2. Two-tone dynamic range illustration from a plot of fundamental to two-tone third order distortion

REFERENCES

[1] D. M. Cutrer, J. B. Georges, T. H. Le, and K. Y. Lau, "Dynamic-Range Requirements for Analog Fiber-Optic Links in Fiber-Fed Wireless Microcells," *OFC'95, San Diego, CA*, Paper ThF1, pp. 242–243, 1995.

[2] W. I. Way, "Optical Fiber-Based Microcellular Systems: An Overview," *IEICE Trans. Commun.*, vol. E76-B, pp. 1091–1102, Sept. 1993.

[3] J. Namiki, M. Shibutani, W. Domon, T. Kanai, and K. Emura, "Optical Feeder Basic System Design for Microcellular Mobile Radio," *IEICE Trans. Commun.*, vol. E76-B, pp. 1069–1076, Sept. 1993.

[4] T. S. Chu and M. J. Gans, "Fiber-Optic Microcellular Radio," *IEEE Trans. Vechicular Technol.*, vol. 40, pp. 599–606, Aug. 1991.

[5] J. Smith, *Modern Communication Circuits.* McGraw Hill, 1986.

[6] W. C. Y. Lee, *Mobile Cellular Telecommunications Systems.* McGraw Hill, 1990.

[7] R. Ohmoto and H. Ohtsuka, "Performance of FM Double Modulation for Subcarrier Optical Transmission," *IEICE Trans. Commun.*, vol. E76-B, pp. 1152–1157, Sept. 1993.

[8] C. K. Chan and L. K. Chen, "Efficient Frequency Assignment Scheme for Intermodulation Distortion Reduction in Fiber-Optic Microcellular Systems," *Electron. Lett.*, vol. 30, pp. 1831–1832, Oct. 1994.

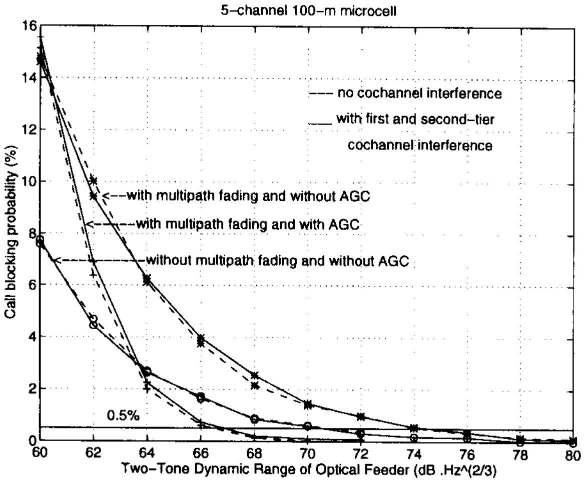

Fig. 3. Call blocking probability versus different link dynamic ranges for a 5-channel 100-m microcell system (Dynamic range penalty is 4dB)

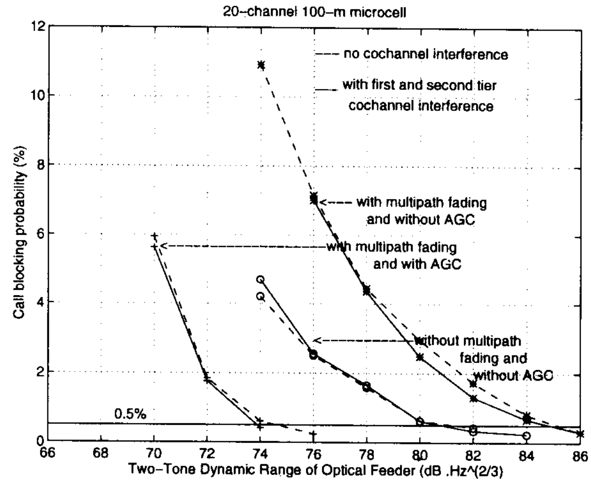

Fig. 5. Call blocking probability versus different link dynamic ranges for a 20-channel 100-m microcell system (Dynamic range penalty is 4dB)

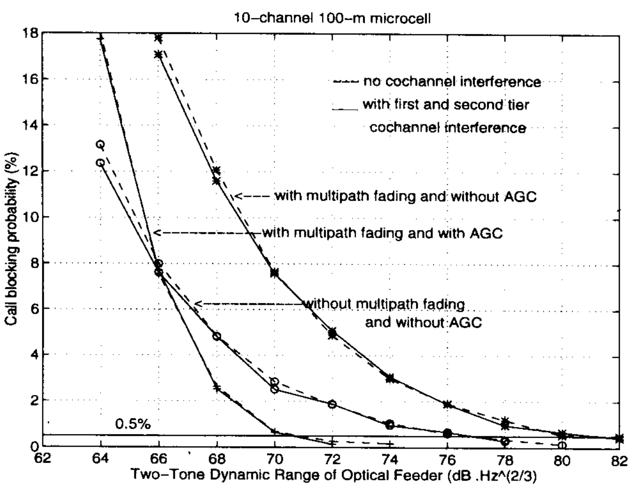

Fig. 4. Call blocking probability versus different link dynamic ranges for a 10-channel 100-m microcell system (Dynamic range penalty is 4dB)

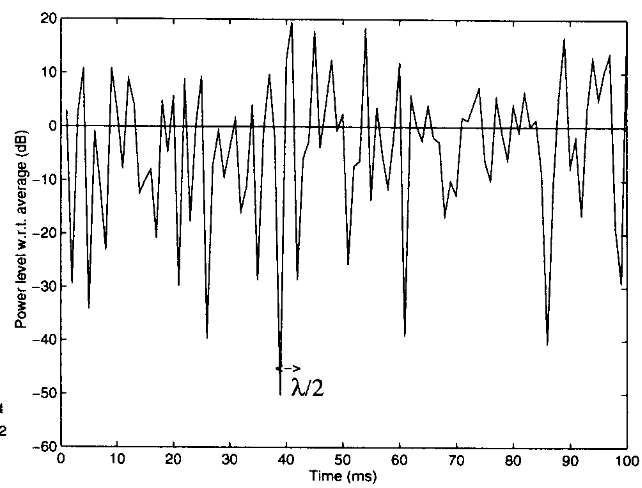

Fig. 6. A typical fading signal received while the mobile unit is moving at 100m/s @900MHz where λ is the carrier wavelength